RECOMMENDATION ITU-R SF.1320

MAXIMUM ALLOWABLE VALUES OF POWER FLUX-DENSITY AT THE SURFACE OF THE EARTH PRODUCED BY NON-GEOSTATIONARY SATELLITES IN THE FIXED-SATELLITE SERVICE USED IN FEEDER LINKS FOR THE MOBILE-SATELLITE SERVICE AND SHARING THE SAME FREQUENCY BANDS WITH RADIO-RELAY SYSTEMS

(Questions ITU-R 219/4 and ITU-R 201/9)

(1997)

The ITU Radiocommunication Assembly,

considering

a) that the World Radiocommunication Conference (Geneva, 1995) (WRC-95) allocated certain frequency bands to the use in the space-to-Earth direction by feeder links for non-geostationary-satellite systems in the mobile-satellite service (MSS) on a shared basis with the fixed service (FS);

b) that, because of such sharing, it is necessary to ensure that emissions from satellites do not cause unacceptable interference to radio-relay systems;

c) that radio-relay systems can be satisfactorily protected from the emissions from satellites by placing suitable limits on the power flux-density (pfd) in a reference bandwidth produced at the surface of the Earth;

d) that in the bands which had been allocated before 1995 to the Earth-to-space direction of the fixed-satellite service (FSS), the additional use in the space-to-Earth direction by feeder links for non-geostationary-satellite systems in the MSS should not introduce a significant increase of interference to radio-relay systems;

e) that, nevertheless, any limitations of the pfd produced at the surface of the Earth should not be such as to place undue restrictions on the design of feeder links for non-geostationary-satellite systems in the MSS;

f) that the earth stations of two non-geostationary (non-GSO) MSS systems operating in the 19.3-19.6 GHz band for their feeder links, space-to-Earth and/or Earth-to-space, cannot be co-located even though they operate on opposite polarization, because the feeder links require a high link margin to achieve the desired link availability;

g) that a non-GSO MSS system operating in the 19.3-19.6 GHz band must use spot beams to achieve their desired G/Ts and e.i.r.p.s. Therefore, there is very low probability that an FS receiver will receive significant interference from more than one non-GSO MSS feeder link system,

further considering

a) that Resolution 119 (WRC-95) instructed the ITU-R to study possible modification of the pfd limits at the surface of the Earth in the 19.3-19.6 GHz band applicable to feeder links of non-geostationary-satellite networks in the MSS, keeping in view the different rain characteristics in many parts of the world;

b) that No. S21.16.7 of the Radio Regulations (RR) states that the pfd limits in the band 6 700-6 825 MHz are subject to review by the ITU-R,

recommends

1 that, in frequency bands in the range 6.7 to 19.6 GHz shared between feeder links of non-geostationary-satellite systems in the MSS and radio-relay systems, the maximum pfd (see Note 1) produced at the surface of the Earth by emissions from a satellite, for all conditions and methods of modulation, should not exceed:

1.1 in the band 6 700-6 825 MHz, in any 1 MHz band:

-137	dB(W/m^2)	for $\theta \leq 5°$
$-137 + 0.5 (\theta - 5)$	dB(W/m^2)	for $5° < \theta \leq 25°$
-127	dB(W/m^2)	for $25° < \theta \leq 90°$

1.2 in the band 6 825-7 075 MHz:

1.2.1 in any 4 kHz band:

−154	$dB(W/m^2)$	for	$\theta \leq 5°$
$-154 + 0.5 (\theta - 5)$	$dB(W/m^2)$	for	$5° < \theta \leq 25°$
−144	$dB(W/m^2)$	for	$25° < \theta \leq 90°$

1.2.2 and in any 1 MHz band:

−134	$dB(W/m^2)$	for	$\theta \leq 5°$
$-134 + 0.5 (\theta - 5)$	$dB(W/m^2)$	for	$5° < \theta \leq 25°$
−124	$dB(W/m^2)$	for	$25° < \theta \leq 90°$

1.3 in the band 19.3-19.6 GHz, in any 1 MHz band:

−115	$dB(W/m^2)$	for	$\theta \leq 5°$
$-115 + 0.5 (\theta - 5)$	$dB(W/m^2)$	for	$5° < \theta \leq 25°$
−105	$dB(W/m^2)$	for	$25° < \theta \leq 90°$

where θ is the angle of arrival of the radio-frequency wave (degrees above the horizontal plane);

2 that the aforementioned limits relate to the pfd and angles of arrival which would be obtained under free-space propagation conditions;

3 that the information contained in Annex 1 should be used as guidance for the use of this Recommendation.

NOTE 1 – Definitive limits applicable in shared frequency bands are laid down in Table S21-4 of Article S21 of the RR. Study of these limits is continuing which may lead to changes in the recommended limits.

ANNEX 1

Interference from non-GSO MSS feeder-link satellites to stations in the FS

1 Explanation of interference

1.1 Highest level of interference

The highest level of interference occurs when a non-GSO MSS feeder link satellite is within the main beam of a terrestrial system antenna. If the non-GSO satellite antenna is considered having a symmetrical gain pattern along the satellite nadir axis, the highest level of interference will be identical for every affected azimuth.

For a given non-GSO constellation, percentage of interference, duration of interference and mean time between interference events will, on the other hand, be very dependant on FS latitude and FS link azimuth as explained in the following section.

1.2 Statistics of worst case interference

The worst case interference is from azimuth directions where the probability of exceeding a certain interference level is at its maximum. Depending on orbital parameters (altitude, inclination) and FS station latitude and elevation, there are one to four worst case azimuths. The smaller the geocentric angle between the FS station and the satellite, the greater will be the off-axis angle and hence the better will be the discrimination against interference. Furthermore most of those terminals will not point to the worst case azimuths and in some cases there are azimuth directions where the satellite would not appear within the main beam of an FS station.

From geometrical considerations of a hypothetical 12 hop FS radio-relay network and of one MSS constellation (12 satellites/3 planes/47.5° inclination/10 000 km height) the following would characterize the worst case interference scenario:

– the maximum number of satellites simultaneously visible to any FS station is not greater than five;
– no individual terrestrial terminal will receive interference via its main beam from more than one satellite at a time and it is improbable that a 1 000 km multiple hop link will receive main beam interference from more than one satellite at a time;
– whenever a satellite interferes via the main beam of a particular microwave terminal, the same satellite will interfere via the side-lobes of the other terminals. This is due to:
  – different azimuth-elevation angle,
  – the Earth's curvature;
– the likelihood of simultaneous main beam interference entries to two terminals of the same radio-relay link may be considered, in the worst case in the hypothetical 12 hop system;
– in the worst case only every other hop can operate on the same frequency.

2 Methodology to determine the fractional degradation in performance (FDP)

2.1 Non-diversity FS systems

Annex 2 of Recommendation ITU-R F.1108 provides a method to calculate the FDP for non-diversity FS systems. The method relates the fraction of time, f_i, that a digital FS receiver experiences an interference level, I_i, to a percentage increase in outage, which is a form of degradation in performance.

In equation form:

$$FDP = \sum \frac{I_i f_i}{N_T} \tag{1}$$

where N_T is the FS thermal noise and the summation is taken over the entire simulation time.

For non-diversity systems in the presence of Rayleigh fading, the outage time is inversely proportional to the fade margin. Since the fade margin is inversely proportional to the total noise (noise plus interference), the outage is directly proportional to the total noise and hence the increase in the total noise due to interference is proportional to an increase in outage or a degradation in performance. This is the basis for equation (1).

2.2 FS systems employing diversity

For a FS system with diversity in the presence of Rayleigh fading, the outage time is inversely proportional to the square of the fade margin and hence the increase in outage is proportional to the square of the increase in total noise.

For diversity systems, the FDP is given as:

$$FDP = \sum [(1 + I_i / N_T)^2 - 1] f_i \tag{2}$$

$$= \sum f_i \left[2 I_i / N_T + \left(I_i / N_T \right)^2 \right] \tag{3}$$

For systems utilizing switched diversity, the above equations are sufficient to characterize FDP. For systems utilizing maximum power combining diversity, one can go a further step by considering the case where the interference arrives at the two antennas such that there is a phase difference, φ, between the two entries of I_i, which can be approximated as follows:

$$I_i / N_T = 2(I_{oi} / N_T) \cos^2(\varphi/2) \tag{4}$$

where I_{oi} is the interference power of each antenna. This equation shows that the level of the total interference is a function of φ. We would evaluate the average effect of interference as follows:

$$(I_i / N_T)_{av} = 1/2\pi \ (I_{oi} / N_T) \int_0^{2\pi} 2\cos^2(\varphi/2) \, d\varphi$$

$$= I_{oi} / N_T \tag{5}$$

$$(I_i / N_T)^2_{av} = 1/2\pi \ (I_{oi} / N_T)^2 \int_0^{2\pi} 4\cos^4(\varphi/2) \, d\varphi$$

$$= 3/2 \ (I_{oi} / N_T)^2 \tag{6}$$

Equation (5) shows that the average value (*av*) of I_i / N_T is the same as I_{oi} / N_T, while equation (6) shows that the average value of $(I_i / N_T)^2$ is 1.5 times of $(I_{oi} / N_T)^2$. Therefore, equation (3) can be rewritten as follows:

$$FDP = \sum f_i \left[(2I_{oi} / N_T) + 3/2 \ (I_{oi} / N_T)^2 \right] \tag{7}$$

However, the following analyses have only used equation (3) to model diversity.

2.3 FS interference criteria

Recommendation ITU-R F.1094 recommends a performance degradation criterion of 10% for services shared on a co-primary basis. Recommendation ITU-R SF.357 specifies interference criteria into analogue radio-relay routes. Recommendation ITU-R SF.1005 recommends that for shared bands allocated in both directions to the FSS (GSO only) the pertinent interference criterion be more stringent by the following amounts:

10-15.4 GHz	: 7 dB
15.4-20 GHz	: 5 dB
Above 20 GHz	: 3 dB

Recommendation ITU-R SF.1005 does not pertain to frequency bands below 10 GHz due to the fact that most bands below 10 GHz are heavily used by the FS, and thus, reverse band working is generally not feasible in these bands. While Recommendation ITU-R SF.1005 deals only with GSO FSS, it is recognized that similar concepts would be applicable to non-GSO FSS.

In the bidirectionally allocated FSS bands that have significant usage in both directions, it is recognized that some tightening of the FDP criterion of 10% would be required when considering interference from reverse-band-working non-GSO MSS feeder links.

3 Feasibility of sharing

Computer simulations were performed using the characteristics of various satellite constellations in order to determine the feasibility of co-frequency sharing with radio-relay systems. For all cases examined, it was concluded that the satellite constellations can share with most analogue and digital radio-relay systems. This conclusion was based on the evaluation of interference to an FS station from satellite constellations.

4 Relevance of Recommendation ITU-R SF.358

It can be shown that the pfd limits of Recommendation ITU-R SF.358 can result in interference from GSO satellites greater than noise in radio-relay system receivers. However the application of such measures as pointing the radio-relay beam several degrees away from GSO orbit ameliorates the interference thus facilitating FS/FSS GSO sharing.

However in the case of non-GSO MSS, the sharing with the FS will take place successfully with the application of a pfd limit, which in fact generates interference that exceeds the thermal noise for short periods of time because the affected receiver will not usually experience fading at the same time that it is receiving this high level of interference. As a result, even though this boresight interference event cannot be avoided, the FDP criterion of 10% or a smaller value can still be satisfied. Therefore Recommendation ITU-R F.1108 is considered to be a more appropriate approach.

5 Applicability of pfd limits of Recommendation ITU-R SF.358

This section examines the appropriateness of applying Recommendation ITU-R SF.358 pfd limits to a non-GSO MSS satellite. First, the simulations are performed assuming a pfd mask equal to the Recommendation ITU-R SF.358 pfd limits (or the closest available). The adequacy of the pfd mask to protect the FS systems in different frequency bands is examined with reference to the protection criteria mentioned in § 2.3. Different pfd values are then derived. Some of the assumptions and properties of deriving pfd values from an FDP calculation are then examined to assess their sensitivity. Revised pfd limits are then proposed for inclusion in the main text of this Recommendation.

5.1 Pfd limits

The pfd limits used in this study are given below (see Recommendation ITU-R SF.358).

7 GHz: –152/–142 dB(W/m^2 in 4 kHz)

19 GHz: –115/–105 dB(W/m^2 in 1 MHz)

5.2 7 GHz sharing studies

The FDP of the FS station is determined but the satellite interference is calculated from a pfd mask. For each time instance, the angle of arrival for each visible satellite is calculated and the corresponding pfd determined. The interference power from each satellite is then calculated as follows:

$$I_t = pfd + 10 \log (\lambda^2/4\pi) + G_{FS} - \text{Feeder Loss}$$

5.2.1 7 GHz assumptions

– The FS antenna radiation pattern was taken from Recommendation ITU-R F.699-3 (Geneva, 1995). Note 6 to that Recommendation was applied.

– No atmospheric attenuation was taken into account.

– The FS elevation angle was assumed to be 3°.

– No polarization discrimination was taken into account.

– FS systems were assumed to employ diversity.

– Satellite constellations are assumed as follows:

LEO D: 48 satellites/8 planes/52° inclination/1 414 km altitude

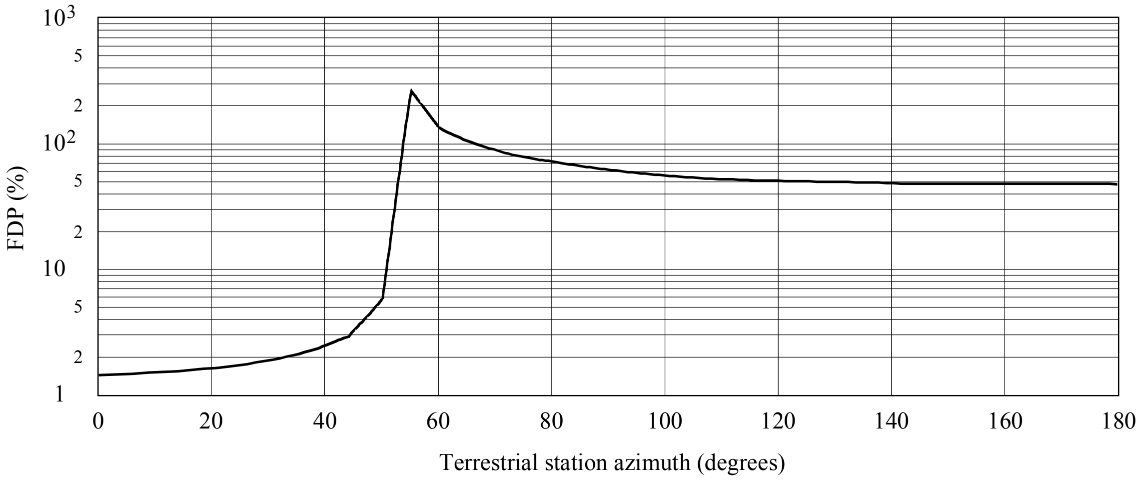
LEO F: 10 satellites/2 planes/45° inclination/10 355 km altitude.

5.2.2 7 GHz results

Figures 1 and 2 show the fractional degradation in performance due to the LEO-D and LEO-F non-GSO MSS constellations, assuming they generate pfd limits on the surface of the Earth stated above. The FS station is assumed to be located at 40° latitude.

FIGURE 1

FDP due to LEO D; FS at 40° N



7 GHz; PFD = –152/–142 dB(W/m^2 in 4 kHz)

Interference is calculated from Recommendation ITU-R SF.358 pfd limits.

LEO D: 48 satellites/8 planes/52° inclination/1 414 km altitude

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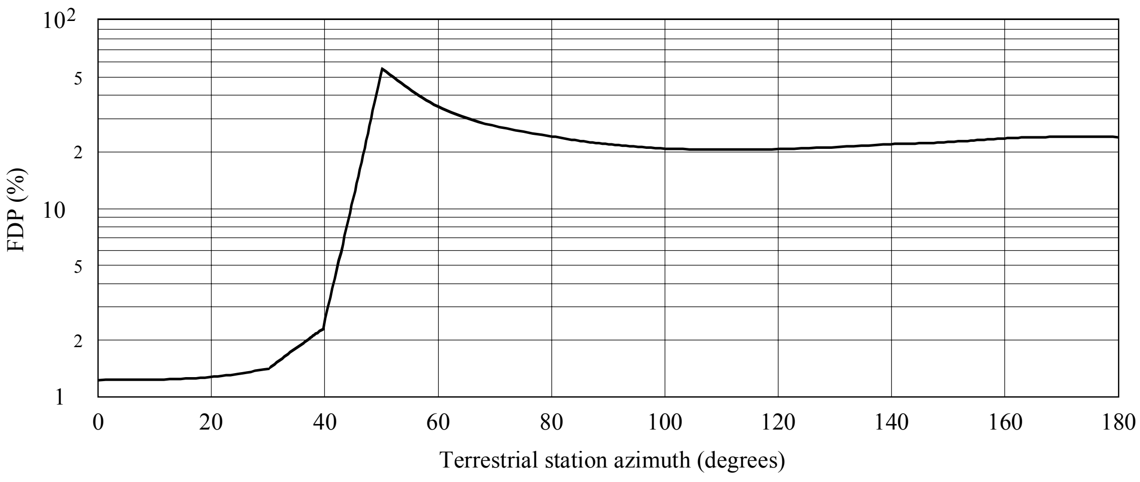
FIGURE 2

FDP due to LEO F; FS at 40° N



7 GHz; PFD = –152/–142 dB(W/m^2 in 4 kHz)

Interference is calculated from Recommendation ITU-R SF.358 pfd limits.

LEO F: 10 satellites/2planes/45° inclination/10 355 km altitude

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The following observations are applicable to the figures:

– the existing Recommendation ITU-R SF.358 pfd limits at 7 GHz band are not sufficient to protect the FS systems with diversity, which is the normal practice. However, these limits would be sufficient for the protection of FS systems without diversity;

– there can be a wide range of FDP values for any one constellation at any one frequency band, especially for those orbits with inclination much less than 90°.

5.2.3 Discussion of appropriate non-GSO MSS feeder-link pfd limits

In this section, pfd limits which adequately protect FS systems for the majority of cases are proposed. The philosophy behind their derivation is given below.

At 7 GHz, assuming that the FSS is allocated in both directions, it is recognized that there should be a tightening of the FDP criterion by some undetermined amount. However, since there can be a large deviation in the FDP for any one constellation due to different FS pointing azimuths, it would seem that some balance can be achieved between the worst case FDP and an “average” FDP for all azimuths. That is, it does not seem appropriate to select a set of pfds such that the worst case azimuth meets a very stringent criterion (e.g. 1%) given the large deviations observed for some constellations.

In order to initiate discussion by deriving new pfd values (to be used as limits), a peak FDP criterion of 4% has been used which provides some balance between Recommendation ITU-R SF.1005 and the large deviations observed. This is equivalent to an increase in protection of 4 dB for the worst case azimuth. The LEO D constellation has been used to determine a possible set of pfd limits and then applied to the other constellation type. Using trial and error, pfd values of –162/–152 dB(W/m^2 in 4 kHz) were found to not exceed the assumed 4% criterion. The 10 dB escalation between the high arrival angle and the low arrival angle is purely arbitrary, but the effect of the escalation is examined in § 5.2.4.4.

Figures 3 and 4 show the results obtained for LEO-D and LEO-F non-GSO feeder-link MSS constellations using the following pfd values at the 7 GHz:

–162/–152 dB(W/m^2 in 4 kHz) at 7 GHz band.

These values, when appropriately weighted with the effect of different assumptions, should lead to a relaxation of these values and ultimately to a set of pfd limits for inclusion in the main text of this Recommendation.

FIGURE 3

FDP due to LEO D; FS at 50° N

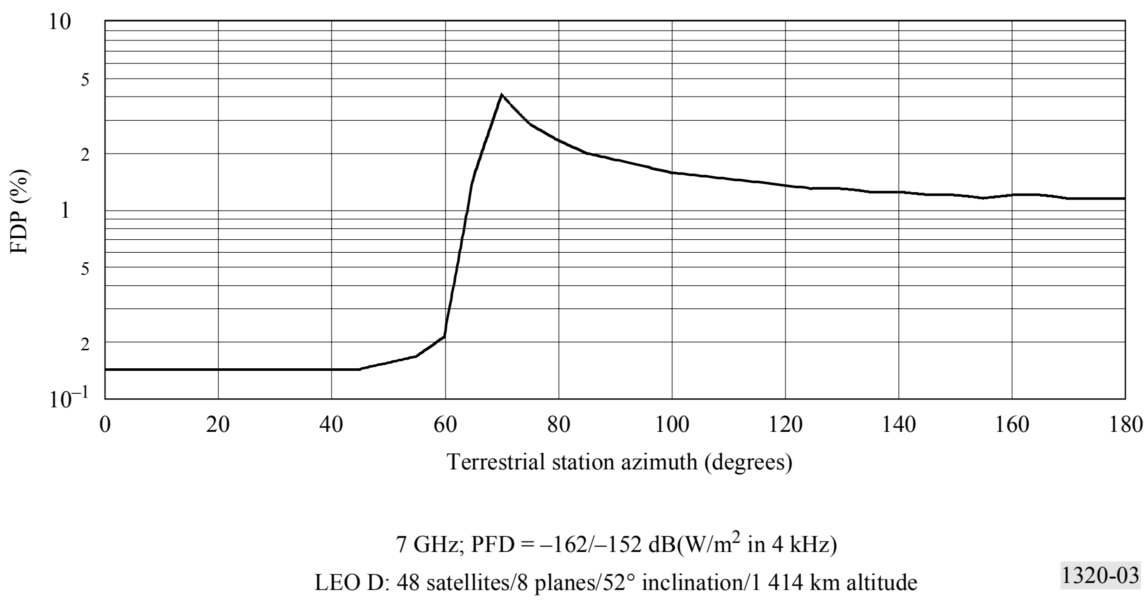


FIGURE 4

FDP due to LEO F; FS at 50° N

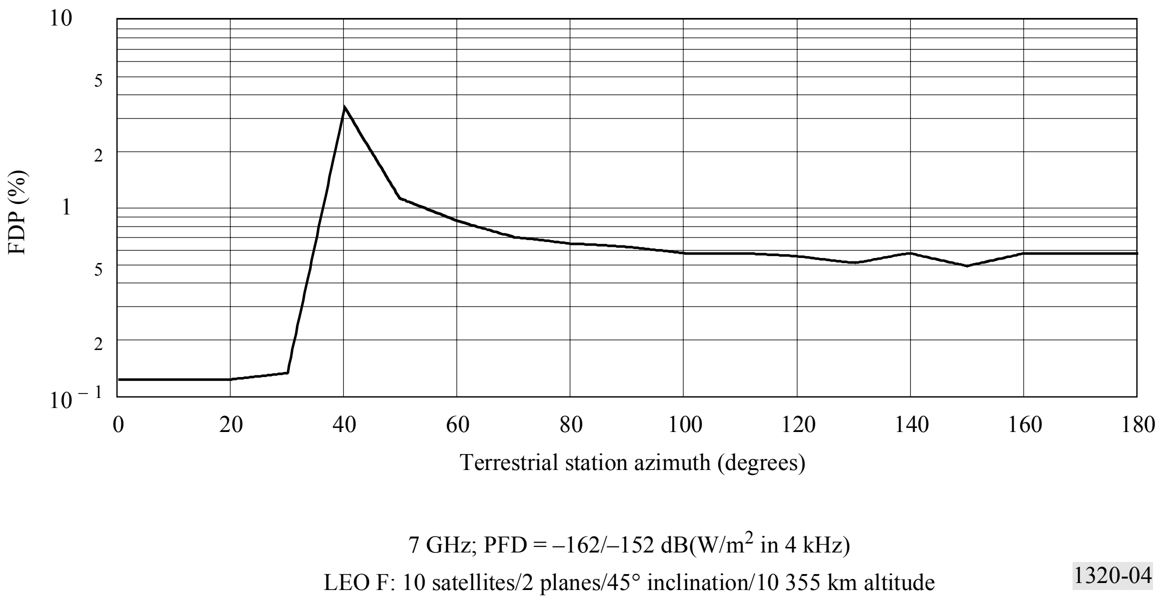
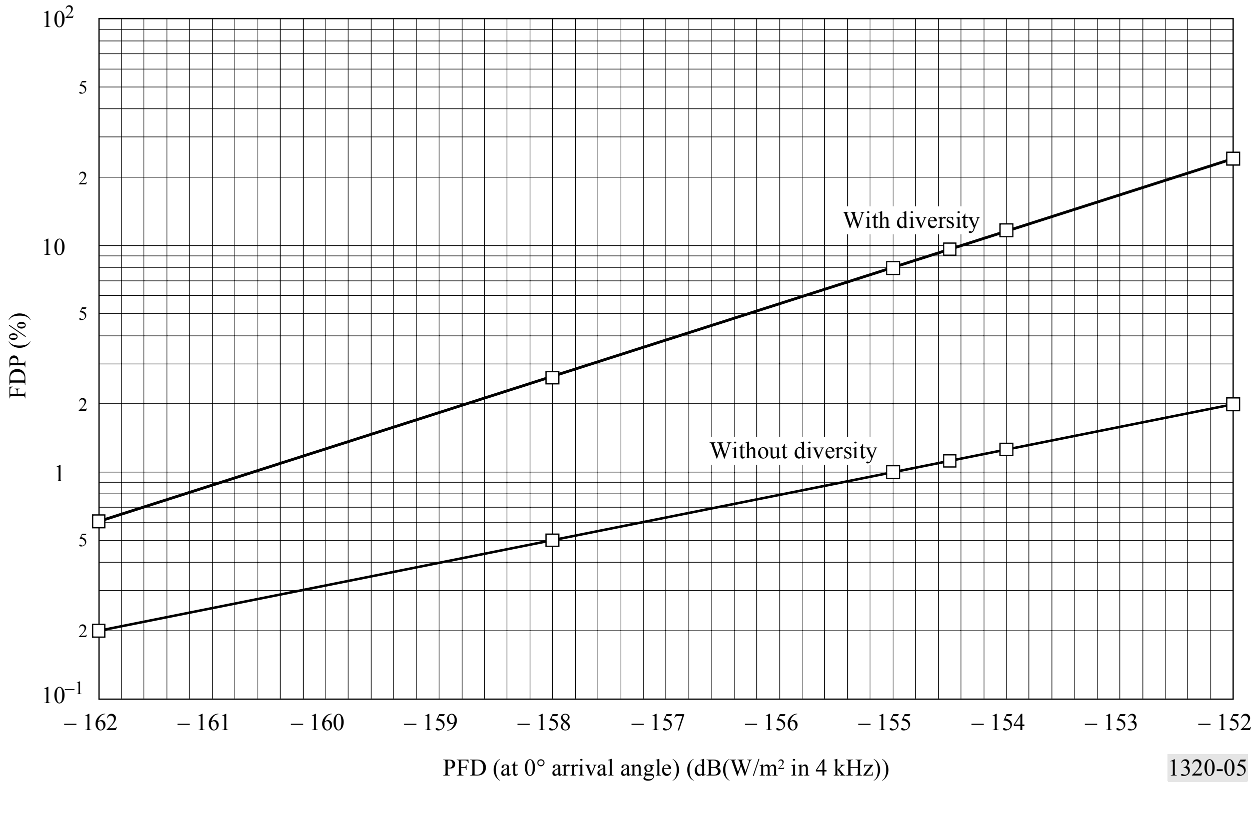


Figure 5 shows the result of another study simulating the entire LEO-F constellation and FS stations with and without diversity (i.e. the FDP given by equations (1) and (3) at the worst case azimuth). This shows the peak FDP value varying with different PFD values (the indicated PFD values refer to the 0° arrival angle).

FIGURE 5

FDP (maximum values) caused from LEO F constellation into a FS station (3.7 m)

(Latitude 20° N, worst case azimuth 48.5°)



5.2.4 Effect of assumptions

Some of the important assumptions that were used are:

– FS latitude at 50°,

– FS elevation angle of 3°,

– no polarization discrimination,

– 10 dB escalation between the high arrival angle and low arrival angle,

– peak RBW FDP of 4%,

– use of a pfd mask.

It is desirable to study the effects of each of these assumptions to examine their sensitivity to the pfd limits derived from an FDP calculation or to measure their degree of conservatism.

5.2.4.1 FS latitude at 50°

It is known that there is a worst case latitude location associated with each non-GSO MSS constellation. Generally, the higher the latitude the more severe the interference. This usually peaks in the latitudes near and around the highest latitude that the non-GSO orbit attains.

If a satellite constellation has an inclination of about 50°, the choice of 50° FS latitude seems proper and reasonable. Therefore, there should be no relaxation of the suggested pfd levels based on the 50° latitude assumption.

5.2.4.2 FS elevation angle

The FS elevation angle used in this section was 3°. This too seems a reasonable assumption given that FS stations tend to have elevation angles between –1° and 3°. It would be tempting to simply take a 1° elevation angle and call that a typical case, but this is actually more conservative than a 3° elevation angle.

For an explanation one must consider the geometry of the situation plus the characteristics of the FDP function itself. The FS antenna main beam forms an elliptical paraboloid where it intersects the orbital shell. The lower the elevation angle of the FS antenna the larger the paraboloid (of course, at 0° elevation, half of the paraboloid will be clipped), and, therefore, the longer it takes for the satellite to traverse the paraboloid. The FDP is both a function of the amount of time the satellite is within the beam of the FS antenna, the discrimination of the FS antenna towards the satellite as a function of time and the satellite interference power (FDP is proportional to If_i).

To a large extent, the FDP is dominated by these short-term high-interference events. Thus, there is a trade-off between the size of the paraboloid, or low elevation angles, and the increased effects of interference at high elevation angles.

The 3° FS elevation angle assumption therefore seems reasonable given the observed phenomenon.

5.2.4.3 Polarization discrimination

It is likely that non-GSO downlink transmissions will have a circular polarization while most FS systems employ linearly polarized signals. There is then a possible 3 dB polarization discrimination when the satellite is in the main beam of the FS antenna, where the FDP is the most sensitive. It, therefore, seems possible to increase the low arrival angle pfd limit by up to 3 dB.

5.2.4.4 Escalation of the pfd mask

A linear 10 dB increase between the 5° arrival angle and 25° arrival angle pfd limit has been assumed.

Increasing the high arrival angle limit by 3 dB has little effect at any azimuth.

It is concluded that the FDP is very sensitive to the low arrival angle pfd but increases of the order of 3 to 6 dB of the high arrival limit can probably be tolerated such that it is possible to accept an increase as small as 4 dB. In order to fashion a pfd mask which takes into account the actual roll off of many non-GSO feeder-link MSS satellite antenna patterns, a 6 to 10 dB increase from the low arrival angle pfd limit is considered appropriate.

5.2.4.5 Reverse band working FDP criterion

An FDP criterion of 4%, which is equivalent to an increase in protection of 4 dB, has been suggested earlier. Increasing the low arrival angle to –161 dB(W/m^2 in 4 kHz) at 7 GHz band will result in an FDP of approximately 6% or an increase in protection of 2.2 dB. Increasing the low arrival angle to –160 dB(W/m^2 in 4 kHz) results in a peak FDP of 8% (1 dB tightening) which is not considered acceptable.

Each non-GSO constellation examined produces peak FDP values at certain azimuths while other azimuths experience reduced FDP values. Noting this phenomenon, a 1 dB relaxation of the low arrival angle pfd can be accommodated.

5.2.4.6 Use of a pfd mask

A pfd mask is inherently conservative. It can be a valid regulatory/technical device, but it usually bears little resemblance to an actual satellite antenna pattern. Using a pfd mask as opposed to an actual satellite antenna pattern causes more interference to be assessed at most angles of arrival than will actually occur. Since this extra calculated interference is most significant between 0° and 5° arrival angle, but many satellites will employ global beams with little roll off in this area, it is suggested that a 1-2 dB increase in the low arrival angle pfd can be accommodated.

5.2.4.7 Multiple non-GSO MSS feeder-link networks

The ITU-R has reached the conclusion that two non-GSO MSS feeder-link networks can share on a co-coverage, co-frequency basis. While no simulations have analysed this scenario, it is deemed appropriate to tighten both the low and high arrival angles by 3 dB. Note that this assumes that the non-GSO MSS feeder-link networks are operating in the same direction.

5.2.5 7 GHz summary

From the preceding discussion, there are various factors which can lead to different pfd values than the ones stated in § 5.2.3. The majority of the assumptions are conservative (notably the lack of polarization discrimination), implying a relaxation of these pfd values is possible. Taking into account new and emerging usage of the fixed service, as well as future non-GSO MSS feeder-link requirements, a balance which provides adequate protection to the majority of FS systems plus flexibility to future non-GSO MSS feeder-link networks, can be reached.

Therefore, it is proposed that a 4 dB relaxation of the derived pfd limits of § 5.2.3 is appropriate using a 10 dB escalation between the low and high arrival angle limits to provide added flexibility to future non-GSO MSS feeder-link networks. In addition, the reference bandwidth of 1 MHz is generally appropriate to protect both analogue and digital radio-relay systems. Therefore, for example, –162/–152 dB(W/m^2 in 4 kHz) limit at 7 GHz band in § 5.2.3 can be translated into –134/–124 dB(W($m^2 \cdot$ MHz)) limit.

A separate study, which does not take into consideration any mitigation factors described above, shows that the pfd mask limits cited in the *recommends* 1.2.1, are adequate to protect the FS systems.

5.3 19 GHz sharing studies

5.3.1 19 GHz system parameters

The system characteristics for the fixed service and non-GSO MSS feeder-link used in this study are given in Table 4. The system parameters were taken from Recommendation ITU-R F.758 for the FS.

5.3.1.1 Effects of slant plant path attenuation by atmospheric gases

In the band near 19 GHz, slant path attenuation by atmospheric gases becomes significant. It is a complicated function of various parameters including the frequency and the terrestrial station altitude and elevation angle. But one can expect at least certain decibels of slant path attenuation in the sharing study near 19 GHz.

If the bidirectional use of the frequency band is introduced in the band near 19 GHz, it is necessary to tighten the sharing criteria by some decibels as described in § 2.3. However, it can be concluded that the necessary tightening of the sharing criteria is generally offset by the above slant path attenuation.

5.3.1.2 Technical characteristics of the LEO B satellite system

The LEO B constellation contains 12 satellites in three orbit planes inclined 50° to the equatorial plane. Each satellite is placed in circular orbit at an altitude of 10 355 km. This system uses the 1 610-1 626.5 MHz and 2 483.5-2 500 MHz bands for the mobile return (user-to-satellite) link and the mobile forward (satellite-to-user) link, respectively. The frequency bands 29.1-29.4 GHz and 19.3-19.6 GHz are used for the feeder uplink and downlink, respectively. The satellite payload functions as a simple bent pipe, frequency translating transponder.

The orbital characteristics of the LEO B constellation are given in Table 1. Tables 2 and 3 show the satellite and the earth station communication system parameters.

TABLE 1

LEO B orbit parameters

Number of satellites	12
Number of orbital planes	3
Number of satellites/plane	4
Altitude (km)	10 355
Inclination angle (degrees)	50
Period of orbit (h)	6

TABLE 2

LEO B satellite communication system parameters

Satellite parameter	Feeder link
Receive frequency (Earth-to-space) (GHz)	29.1-29.4
Receive bandwidth (MHz)	300
Receive polarization	LHCP
Antenna coverage	2.2° @ 3 dB
Number of beams	3 steerable antennas
Receive G/T (dB(K^{-1}))	9.5 (peak)
Transmit frequency (space-to-Earth) (GHz)	19.3-19.6
Transmit bandwidth (MHz)	300
Transmit polarization	RHCP
Antenna coverage	3.0° @ 3 dB
e.i.r.p. (dBW)	46.4

TABLE 3

LEO B earth station parameters

Parameter	Earth station
Transmit frequency (Earth-to-space) (GHz)	29.1-29.4
Transmit bandwidth (MHz)	300
Transmit polarization	LHCP
Transmit e.i.r.p. (dBW)	85.9 (peak)
Transmit antenna gain (dBi)	64.8
Receive frequency (space-to-Earth) (GHz)	19.3-19.6
Receive bandwidth (MHz)	300
Receive polarization	RHCP
Receive antenna gain (dBi)	60.8
Receive G/T (dB(K^{-1}))	32.5

TABLE 4

System parameters and pfd limits

Fixed system		
Frequency band (GHz)	17.7-19.7	
System type	O-QPSK	
Capacity (Mbit/s)	44.7	
Channel bandwidth (MHz)	40	
Antenna gain (dBi)	45	
Feeder loss (dB)	3	
Receiver thermal noise (dBW)	–125	
Nominal long-term interference (dBW)	–131	
Non-GSO MSS feeder link system		
System type	LEO A	LEO F
Downlink frequency (GHz)	19.4-19.6	20
Modulation type	FDMA/QPSK	QPSK/TDMA
Orbital altitude (km)	780	10 355
Inclination angle (degrees)	86	50
Number of satellites	66	12
Minimum operating angle (degrees)	8	5

5.3.1.3 Calculation of criteria for acceptable interference

In order to establish the acceptable interference criteria, a value for the level of permissible interference power must be calculated. This value can be determined using equation (4) of Recommendation ITU-R SF.1006 as follows:

$$P_r\left(p_2/n_2\right) = 10\log\left(k\,T_r\,B\right. + 10\log\left(10^{M_s/10} - 1\right) + N_L - W \qquad \text{dBW}$$

The parameters of this equation are defined in Recommendation ITU-R SF.1006.

Reference can also be made to Recommendation ITU-R SF.1005 which deals with sharing between the FS and the FSS in bidirectionally allocated bands. According to this Recommendation, the criteria of maximum permissible interference, both long-term and short-term, should be tighter than those calculated by Recommendation ITU-R SF.1006 by 5 dB for the frequency bands between 15.4 and 20.0 GHz. While Recommendation ITU-R SF.1005 does not explicitly state the satellite type (non-GSO or GSO), none the less that concept is also applicable to non-GSO MSS.

Table 5 shows the parameters used to calculate the threshold interference level.

TABLE 5

Parameters required for the determination of the acceptable interference for a digital receiving fixed station

Frequency range (GHz)		15-40
Service of interfering system		Fixed-satellite
p_2 (%)		0.005
n_2		1
B (Hz)		10^6
J (dB)		0
W (dB)		0
M_s (dB)		25
N_L (dB)		0
Maximum permissible interference power[(1)] (dBW)	P_r (0.005%)	–116 –121[(2)]
	P_r (20%)[(3)]	–147 –152[(2)]

(1) The maximum permissible interference power are calculated using the actual thermal noise level of the FS system given in this study.

(2) This value is used for the frequency band with bidirectional use.

(3) The long-term interference criteria were derived from Table 4.

5.3.1.4 Calculation of interference level into the FS

A computer program was developed to calculate the interference from non-GSO satellites into a terrestrial station. The satellite position is determined based on its orbital parameters using a 2 and 30 s time increment for the LEO A and LEO F, respectively. If the satellite is visible to the FS, then the satellite interference is calculated from the pfd limits using the following equation:

$$I_t = pfd + 10 \log (\lambda^2/4\pi) + G_{FS} - L_{atm} - \text{Feeder Loss}$$

where:

G_{FS}: FS antenna gain in the direction of the satellite (dB)

L_{atm}: atmospheric loss (dB)

pfd: see § 5.1 for the limits.

Since the satellites are assumed to be transmitting all the time in this study, the FS station may experience interference from multiple satellites at the same time.

5.3.1.5 Assumptions

– The FS station is located at 45° N with antenna elevation angles of 0° and 3°.

– The FS antenna pattern is taken from Recommendation ITU-R F.699.

– The simulation time is 30 days.

5.3.1.6 Cumulative interference results

The cumulative distribution of interference power received by the FS station with an antenna elevation of 3° pointing at the worst case azimuth for various non-GSO constellations operating at the minimum required elevation angles are presented in Fig. 6. Figure 7 shows the sensitivity of the FS antenna elevation angle on the interference power using a LEO A constellation operating at the minimum required elevation angle and the FS at elevation angles of 0° and 3°. The impact of the minimum satellite elevation angle on the FS is also studied and the results are shown in Figs. 8 and 9 with all LEO constellations assumed to operate with a 0° minimum angle.

FIGURE 6

Cumulative distribution function of non-GSO interference into FS at worst case azimuth

FS at 45° N

Antenna elevation = 3°

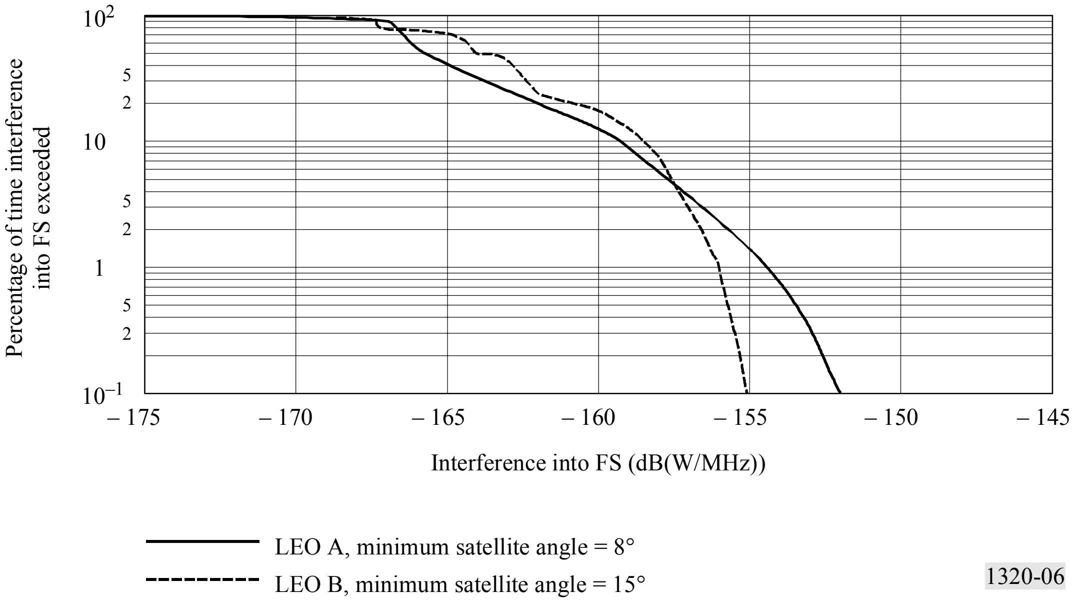


FIGURE 7

Cumulative distribution function of interference from LEO A into FS at worst case azimuth

FS at 45° N

Minimum satellite operating angle = 8°

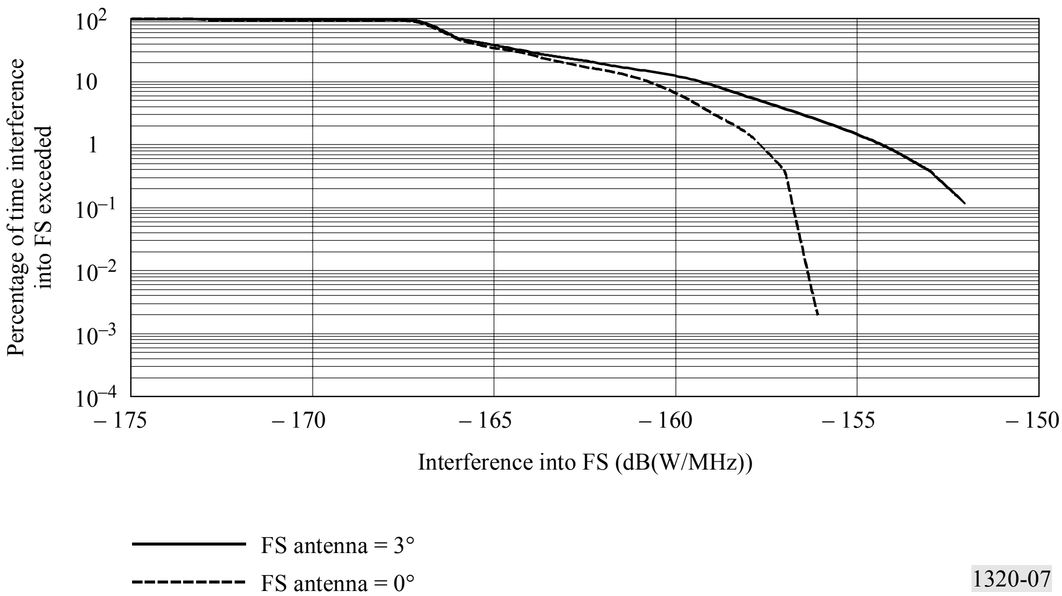


FIGURE 8

Cumulative distribution function of non-GSO interference into FS at worst case azimuth

Minimum satellite operating angle = 0°

FS at 45° N

Antenna elevation = 0°

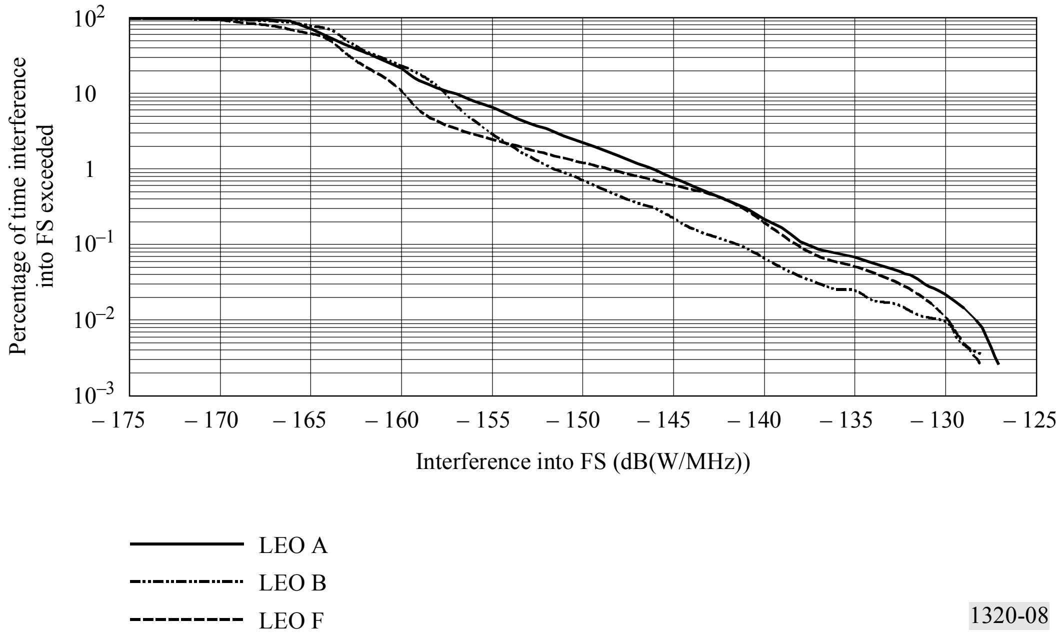


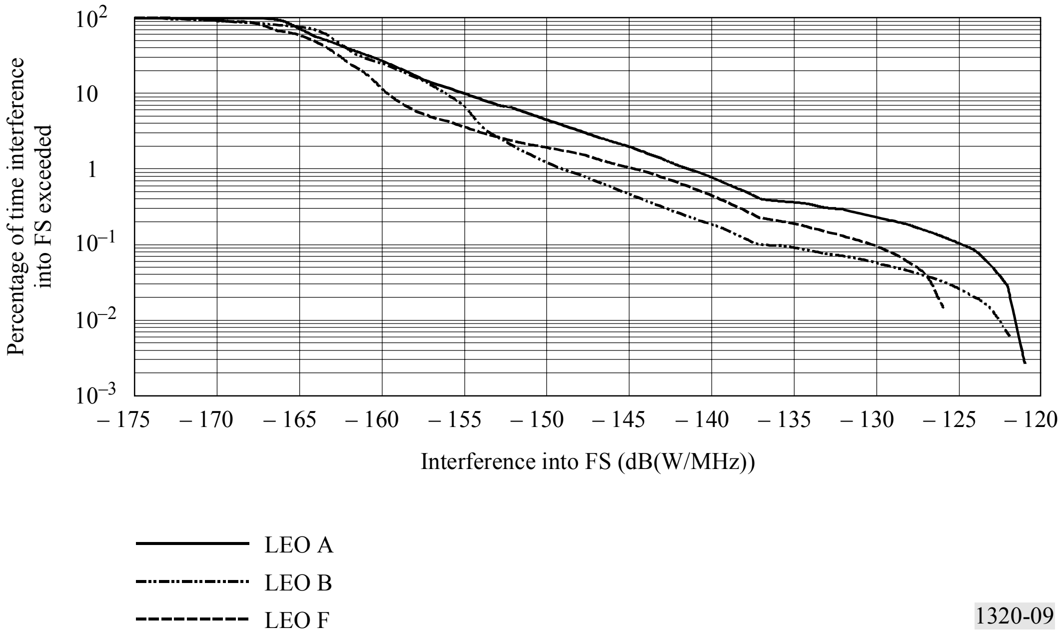
FIGURE 9

Cumulative distribution function of non-GSO interference into FS at worst case azimuth

Minimum satellite operating angle = 0°

FS at 45° N

Antenna elevation = 3°



From the results, it can be observed that for both the unidirectional and bidirectional cases:

– For all the LEO constellations operating with the required minimum elevation angle (as shown in Fig. 6), the received interference power using the pfd values of –115/–105 dB(W/(m^2 · MHz)) in the main text of this Recommendation never exceeds the interference limit for the short term criteria. For the long term criteria, the cumulative time of interference is much lower than the required percentage of time. The worst case is for LEO F with the percentage of time that the interference power exceeds the performance requirement is 0.06% at $I = -147$ dB(W/MHz) (unidirectional case) and 0.55% at $I = -152$ dB(W/MHz) (bidirectional case).

– As the FS antenna elevation angle decreases, the percentage of interference for any given period of time will also decrease. This is due to the FS antenna discrimination. As shown in Fig. 7, using a LEO A constellation, the maximum interference power level for the FS elevation angle of 0° is about 4 dB lower than that for the FS elevation angle of 3°.

– For the satellites operating with a 0° minimum elevation angle (as shown in Figs. 8 and 9), the received interference power is much higher than that for the satellites operating with their actual specified minimum elevation angle. However, even though the interference is higher, it still meets both the long and short term interference criteria for both the unidirectional and bidirectional cases.

5.3.2 FDP methodology

5.3.2.1 FDP at FS receiver

The FDP at the FS receiver, for an azimuth Az, can be calculated as:

$$FDP_{Az} = (1/T_{max}) \sum_{n=min}^{max} \left(10^{\frac{I_{0,t_n} - N_0}{10}} \right) (\Delta t_n)$$

where:

I_{0,t_n}: calculated interference density at time t_n (dB(W/Hz))

N_0: thermal noise density (dB(W/Hz))

Δt_n: time step ($t_n - t_{n-1}$)

T_{max}: duration of the simulation.

I_{0,t_n} can be calculated as:

$$I_{0,t_n} = pfd - 10 \log (4\pi/\lambda^2) - 60 + G_{SF}(\alpha)$$

where $G_{FS}(\alpha)$ is the FS receive antenna gain in the direction of the non-GSO MSS feeder-link satellite.

The separation angle, α, can be calculated as:

$$\alpha = \cos^{-1}\left[\cos(E1)\cos(E2)\cos(A1 - A2) + \sin(E1)\sin(E2)\right]$$

where:

$E1$: FS station elevation angle to LEO B satellite

$A1$: FS station azimuth angle to LEO B satellite

$E2$: FS station elevation angle to another FS station

$A2$: FS station azimuth angle to another FS station.

The LEO B earth station is assumed to be co-located with the FS station, and the LEO B satellite antenna is aimed at the LEO B earth station.

5.3.2.2 Pfd

The LEO B system uses code division multiple access (CDMA) for its access method. Most of the time, the LEO B system operates at a low pfd, typically 10 to 15 dB below the RR limits, which vary between –115 and –105 dB(W/(m^2 · MHz)). The non-GSO MSS feeder links operate at high link availability, typically 99.9% or higher. Depending on the traffic demand and rain zone climate, the LEO B system may operate at the ITU limits for a very small percent of the time.

In this simulation, the pfd mask of –115/–105 dB(W/(m^2 · MHz)) was applied to all satellites of the LEO B constellation. It was also assumed that the LEO B earth station, with multiple antennas, communicates to all satellites in view and is co-located with the FS station.

5.3.2.3 Simulation results for single feeder link system

A simulation of 12 LEO B satellites was performed over a 24-h period, with a time step of 15 s. In our simulation, we assumed the following:

– Characteristics of the FS receiver:
  – Receive frequency: 19.3-19.6 GHz
  – Antenna gain: 42 and 45 dBi
  – Total system noise figure (NF): 5, 7 and 9 dB
  – FS station location: 43.4° N latitude
70.2° W longitude
  – Elevation angle of FS station: 3°
– Minimum operational elevation angle of LEO B system: 5°
– LEO B earth station location: 43.4° N latitude
70.2° W longitude
– No polarization advantage
– FS receive antenna pattern based on Recommendation ITU-R F.699.

The FDP values at the FS receiver for antenna gains of 42 and 45 dBi are shown in Figs. 10 and 11. Based on Figs. 10 and 11, the level of interference at an FS receiver with antenna gain of 42 dBi is slightly higher than the level at an FS receiver with antenna gain of 45 dBi. The reason is that an antenna with 42 dBi gain has slower roll-off than an antenna with 45 dBi gain as shown in Fig. 12.

5.3.2.4 FDP at FS receiver due to two non-GSO MSS forward-band feeder link systems

Sharing studies presented simulation results on frequency sharing between two non-GSO MSS feeder-link systems in the 29/19 GHz bands. Based on these results, earth stations of two non-GSO MSS feeder-link systems cannot be co-located even though they operate on opposite polarization, because the feeder links require a high link margin to achieve the desired link availability. Typical feeder link availability is greater than 99.9%.

In addition, non-GSO MSS feeder links operating in the 29/19 GHz bands must use spot beams to achieve their desired G/Ts and e.i.r.p.s. Therefore, there is a very low probability that the FS receiver will receive interference from more than one non-GSO MSS feeder-link system at any time.

However, for a worst case analysis, the FS receiver is assumed to be located within the satellite 3 dB beamwidth of each non-GSO MSS system and therefore receives interference from both systems simultaneously. If both non-GSO MSS systems operate at the ITU pfd limit and the 3 dB polarization isolation between satellite and terrestrial systems is taken into account, the FDP at the FS receiver is the same as shown in Figs. 10 and 11.

5.3.2.5 Reverse-band (Earth-to-space) non-GSO MSS feeder links sharing with the FS

The sharing between non-GSO MSS feeder links operating in the Earth-to-space direction with FS receivers has not been examined in this study.

FIGURE 10

FDP at the FS receiver due to LEO B constellation (FS station antenna gain = 42 dBi)

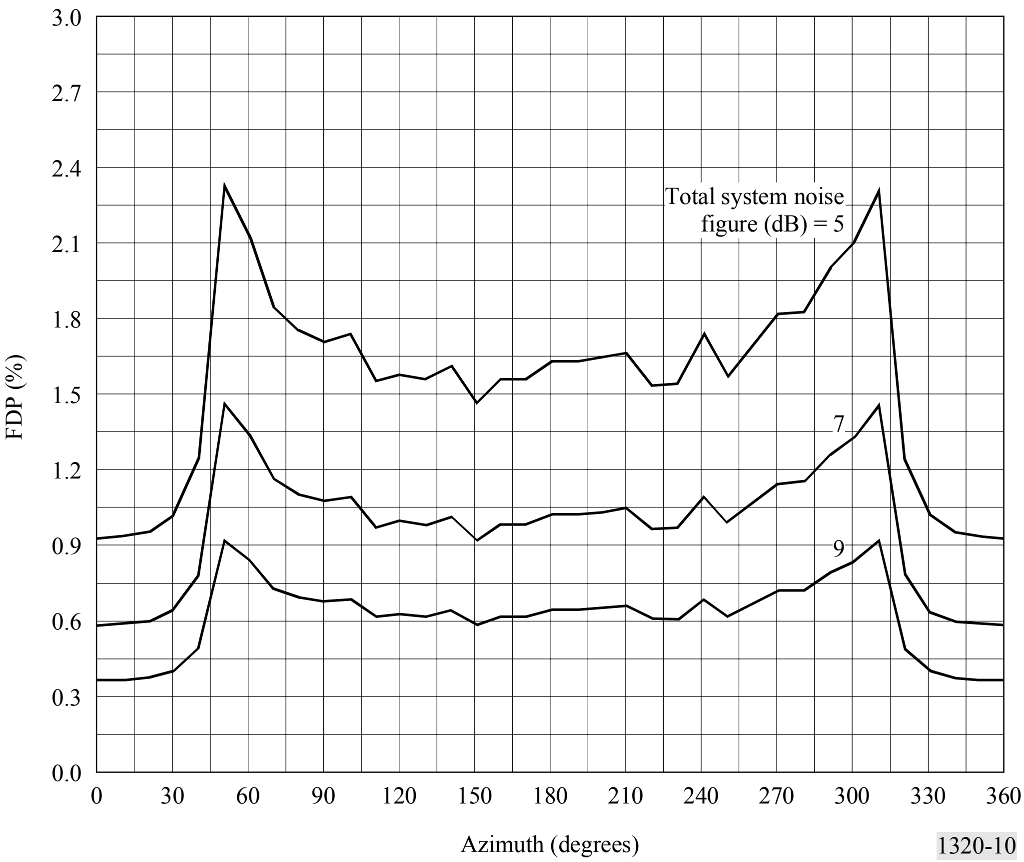


FIGURE 11

FDP at the FS receiver due to LEO B constellation
(FS antenna gain = 45 dBi)

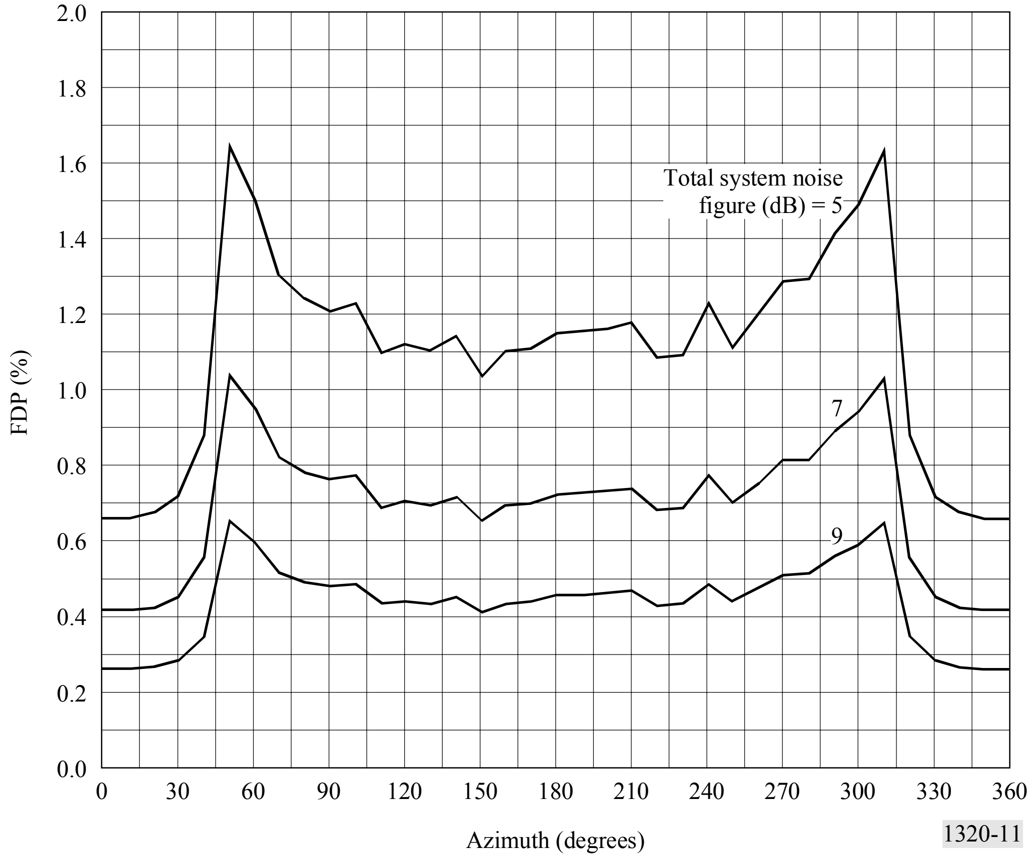


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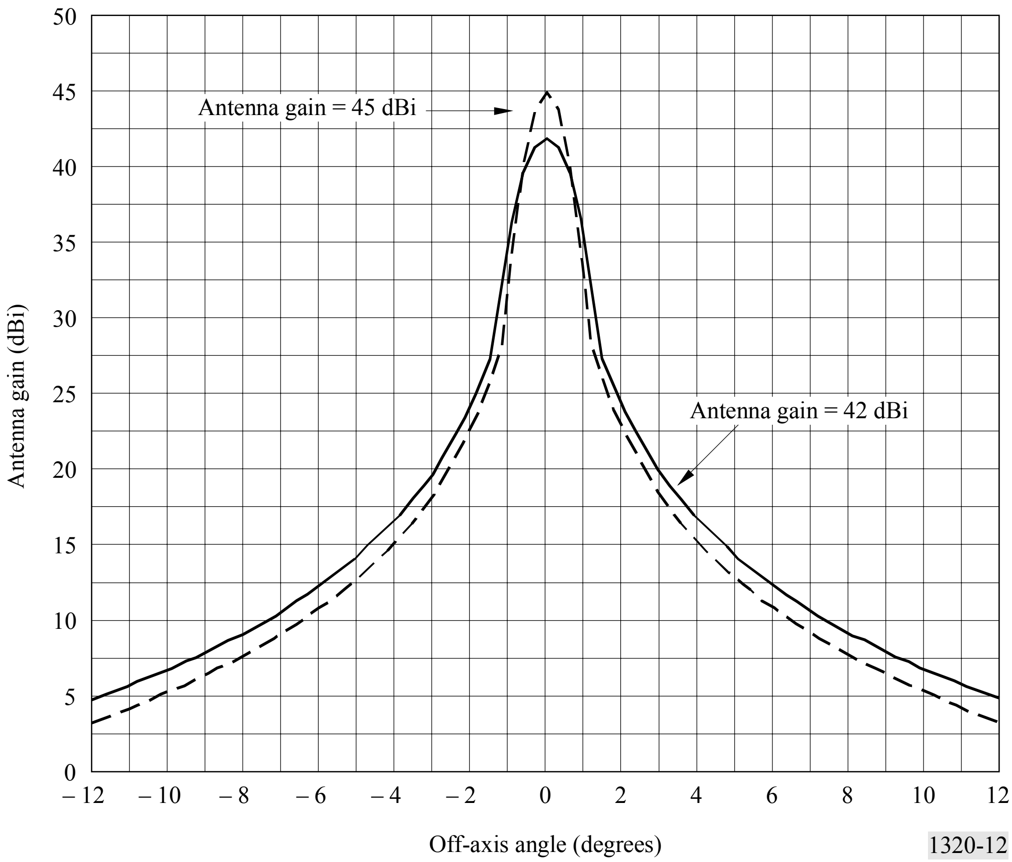
FIGURE 12

FS receive antenna patterns
(See Recommendation ITU-R F.699)



5.3.2.6 Cumulative interference levels for the LEO B system

In addition to the FDP simulations shown above, the cumulative distributions of the interference density (I_0) from the LEO B system at an FS receiver, at FS station elevation angles of 0° and 3°, are shown in Figs. 13 and 14. These results were derived from a computer simulation of the satellite constellation using the following formula to compute I_0:

$$I_0 = pfd - 10 \log (4\pi / \lambda^2) + G_{FS}(\alpha) \qquad \text{dB(W/MHz)}$$

Again, no atmospheric or feeder loss was taken into account.

5.3.3 19 GHz summary

The impact of interference from 19 GHz band non-GSO MSS feeder links operating at the current Article S21 of the RR pfd limits has been examined. The results indicate that the interference will be within acceptable levels. The percentage of time during which the interference exceeds the permissible level is higher for the bidirectional case than for the unidirectional case.

It should be noted that the analysis is performed for an FS station at 45° N pointing in the worst case azimuth direction. The interference level (or the percentage of time interference occurred) may be higher if the FS station is located further north. However, the increase in the interference power should not be significant enough to change the conclusions due to the fact that the interference level is well below the criteria.

The simulation results show that the FDP of an FS system due to the down link of non-GSO MSS feeder link system is below 2%. In this study, it was assumed that the LEO B system operates at the RR pfd limit down to a 5° elevation angle, and that the LEO B earth station communicates to all satellites in view. Also, no polarization isolation was taken into account. Even though the worst case analysis was assumed in the simulation, the FDP at the FS receiver is still less than 2%.

In summary, it can be concluded that the current Article S21 of the RR pfd limits for the 19.3-19.6 GHz band should adequately protect the FS.

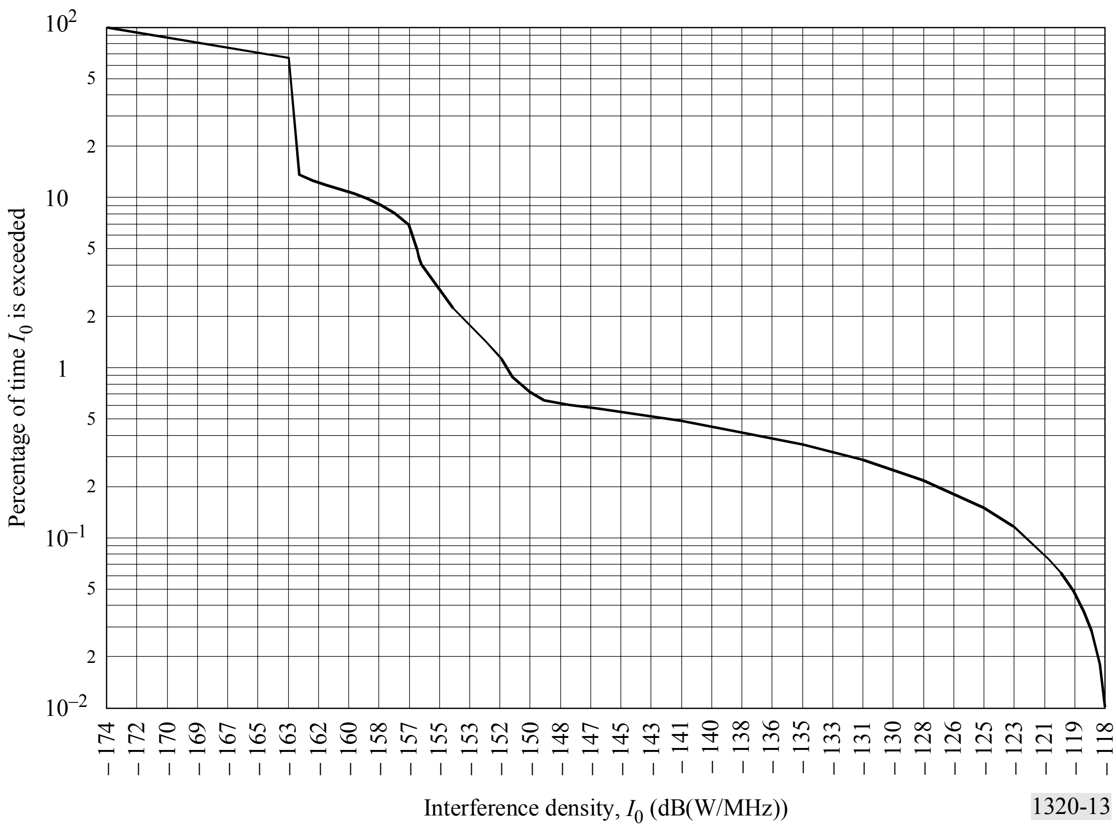
FIGURE 13

Interference density I_0 at FS Rx

FS elevation angle = 0°

LEO B elevation angle = 0°

Worst azimuth



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6 Proposed pfd limits

Based on the analyses of different studies and discussions of mitigating factors (see § 5.2.4), the following pfd limits are proposed to be applicable to each non-GSO MSS satellite operating in a reverse band mode:

6 700-6 825 MHz: –137/–127 dB(W/m^2 in 1 MHz)

6 825-7 075 MHz: –134/–124 dB(W/m^2 in 1 MHz) and –154/–144 dB(W/m^2 in 4 kHz)

where the limit using 4 kHz reference bandwidth is added to provide additional protection for high-capacity analogue radio-relay systems.

For the band 19.3-19.6 GHz, the following limit is appropriate:

19.3-19.6 GHz: –115/–105 dB(W/m^2 in 1 MHz)

The pfd limits listed here are derived on an assumption of two non-GSO MSS feeder-link networks.

FIGURE 14

Interference density I_0 at FS Rx

FS elevation angle = 3°

LEO B elevation angle = 5°